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Life cycle analysis of 4.5 MW and 250 W wind turbines

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ABSTRACT

Electric generation by wind turbine is growing very strongly. However, the environmental impact of wind energy is still a matter of controversy. This paper uses Life Cycle Assessment, comparing two systems: a 4.5 MW and a 250 W wind turbines, to evaluate their environmental impact. All stages of life cycle (manufacturing, transports, installation, maintenance, disassembly and disposal) have been analysed and sensitivity tests have been performed. According to the indexes (PEPBT (primary energy pay back time), CO_2 emissions, etc.), the results show that wind energy is an excellent environmental solution provided first, the turbines are high efficiency ones and implemented on sites where the wind resource is good, second, components transportation should not spend too much energy and, third, recycling during decommissioning should be performed correctly. This study proves that wind energy should become one of the best ways to mitigate climate change and to provide electricity in rural zones not connected to the grid.

Contents

1. Introduction

Presently, wind energy, together with biomass, is one of the most promising renewable energy sources and for sure it is the first one, after hydroelectricity, for green electricity. However, the environmental impact of wind energy is hardly disputed with controversial on the avoided CO_2 emissions and on the primary energy pay back time (PEPBT). This controversial arguments are all the more important in countries, like France, with low carbon electricity generation. It is the reason why, after studying the impact of biogas co-and tri-generation on environment [1], we now address the problem of the environmental impact of wind

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energy. This study will be focussed on France since it is a difficult competition with the present French mix electricity production based on nuclear and hydroelectricity.

In 2007, the worldwide wind power installed amounted 93.7 GW out of which 57 GW from Europe [2]. Europe has been leading in that field since the beginning of this millennium but the recent trend is that USA is since 2006 the first country with respect to new added capacity followed by China [2]. The target assigned in the White Paper for the EU to have 40 GW installed in 2010 will be highly overtaken since, more probably the cumulated installed power should reach 90 GW. Wind power is essential for the EU to increase the share of renewable electricity from 14% in 1997 to 20% in 2020 as targeted by the EU [3]. Wind energy, expected to represent about 5.5% of European electricity production in 2010 and about 12.1% in 2020, will allow to reach that ambitious target.

Previous life cycle assessment (LCA) studies of wind turbines exist. Recently, results of a life cycle assessment have been published based on data related to an Italian wind farm including eleven 660 kW turbines [4]. In this study, the plant ecoprofile is strongly affected by the ecoprofiles of the raw materials that together are responsible for about 70% of the global impacts. Pay back indexes resulted lower than 1 year and the primary energy output is 40–80 times higher than the energy globally consumed during its life cycle. The energy intensity varies for 0.04 to 0.07 kWhprim/kWhe and CO_2 intensity index varies from 8.8 to 18.5 g/kWhe and pay back time, expressed in primary energy, is lower than 1 year.

It is now well recognized that the fact that wind energy does not use fossil fuel is not enough to claim it is definitely a good solution for environment. It is necessary to make sure, through a life cycle assessment, it actually saves emissions. In countries like France where the energy mix generates low carbon electricity, the question arises on the comparison between wind energy and other sources with respect to environmental impact. How long is the period before the energy produced by wind turbine will be completely "green"?

Presently, wind energy is mostly produced through wind farms based on large power turbines but there exists also another trend consisting in the integration of renewable energy in low energy building. Doing so, small turbines are considered [5]. It is the reason why the goal of this work is to compare life cycle assessment for a high power wind turbine (4.5 MW), to be part of a wind farm, and a small one (250 W), to be integrated in a building or to be used on an isolated site.

1.1. Life cycle methodology

Life cycle management is quickly becoming a well-known and often used approach for environmental management. Thanks to Life Cycle Assessment, we are able to evaluate the environmental impacts caused by a product or a process. A life cycle approach involves a cradle-to-grave assessment, where the product is followed from its primal production stage involving its raw materials, to its end use.

The LCA methodology consists of four major steps. The first one is the definition of the goal and scope of the analysis. This includes the definition of a reference unit: all the inputs and outputs are related to this reference. This is called the functional unit, which provides a clear, full and definitive description of the product or service being investigated, enabling subsequent results to be interpreted correctly. The second step is the inventory analysis, also called life cycle inventory (LCI), which is based primarily on systems analysis treating the process chain as a sequence of subsystems that exchange inputs and outputs. Hence, in LCI, the product system is defined, which includes setting the system boundaries, designing the flow diagrams with unit processes, collecting the data for each of these processes and which emissions will occur.

The next step is the impact assessment one. This includes the impacts in terms of emissions and raw material depletions.

The last step is to compare with other processes offering a similar utility and have a critical view of these previous steps. This is referred to as the interpretation step [6–10].

In order to compare environmental impacts we need to select impact categories.

In this paper, authors decided to use a damage approach with the Impact 2002+ method introduced by Jolliet et al. [11]. This method proposes a feasible implementation linking all types of life cycle inventory results via 14 midpoint categories to four damage categories:

- *Climate change*: this category corresponds to the global warming potentials. Midpoints characterization factors for global warming have been taken from the IPCC list [12]. The latest global warming potentials have been used with a 500 years time horizon. Climate change is largely dominated by CO_2 emissions and is expressed in "kgequiv. CO_2".
- *Resources*: it corresponds to the extraction of minerals and fossils fuels. It is expressed in "MJ primary non-renewable energy".
- *Ecosystem quality*: it corresponds to the aquatic and terrestrial ecotoxicity, terrestrial acidification and nitrification, and the land occupation. It is expressed in "PDF.m^2.yr" (Potentially Disappeared Fraction of species per m^2 per year).
- *Human health*: it regroups human toxicity, respiratory effects, ionising radiation, ozone layer depletion and photochemical oxidation. It is expressed in "DALYs" (Disability Adjusted Life Years).

1.2. Environmental and energy evaluation

Evaluation of energy and environmental impacts of a wind turbine need some indicators for comparison with other energy systems. Two types of indicators were calculated: pay back time and intensity index.

1.2.1. Pay back time

In the literature, two pay back times for energy are used. Therefore, herein both were calculated: energy pay back time (EPBT) and primary energy pay back time.

Energy pay back time is defined as the number of years required to recover all the energy invested during the life time of the turbine, i.e. manufacturing, transportation, operation, decommissioning, etc. EPBT is a ratio between primary energy consumed during LCA and wind turbine electricity production per year. Doing so, we compare electricity with primary energy and the comparison is unfair.

For PEBT, the same approach is followed except that, now, this wind turbine electricity production is converted into primary energy necessary to produce electricity. From our point of view, this index is much more consistent than the previous one (EPBT).

For climate change impact, a GHG pay back time is calculated as the ratio between LCA emissions and grid emission to produce the same amount of electricity than the wind turbine. The reference for the grid emission will be discussed later on.

1.2.2. Intensity index

Intensity index is calculated at the end life of the wind turbine. It is the ratio between either the primary energy consumed or the CO_2 emissions, and the electricity production during the wind turbine life time. Theses two intensity indexes are called: energy intensity in kWhprim/kWhe and CO_2 intensity in g CO_2/kWhe.

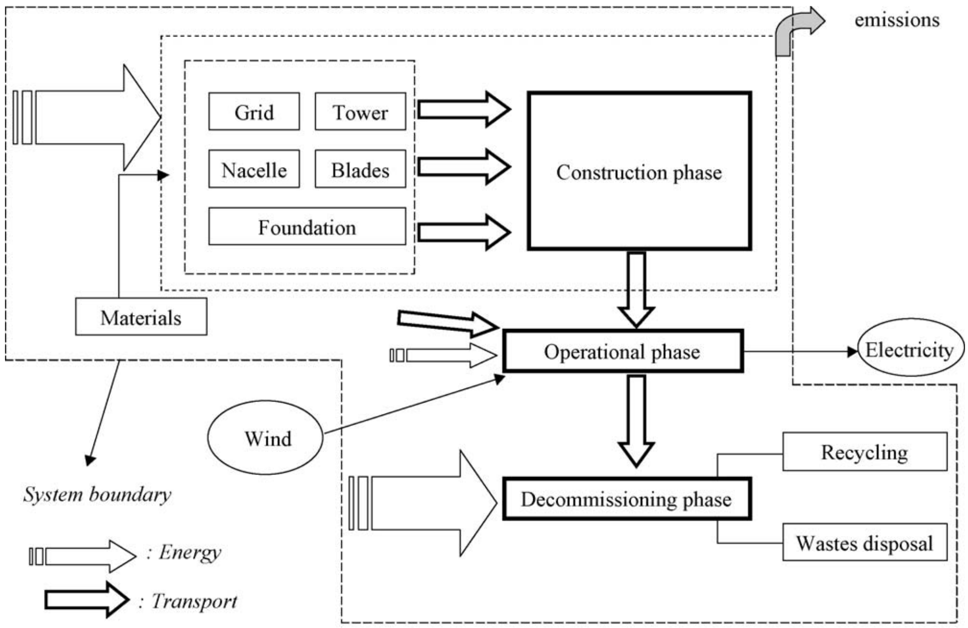

Fig. 1. Life cycle boundary of the 4.5 MW wind turbine.

2. Case study

This study is based on a theoretical comparison between a 4.5 MW wind turbine and a 250 W one. The turbines are supposed to be located in the south of France (end user site). The life cycle of the two wind turbines is considered in three phases: construction, operation by the end user and decommissioning (Figs. 1 and 2). For comparison, the basis is a 1 kWh of electricity produced (kWhe).

2.1. 4.5 MW wind turbine description

Data regarding the manufacturing, installation and use for this turbine refer to the Eclipse Project [13] and results of Ref. [14].

The concrete tower is 124 m high and the rotor diameter is 113 m with three blades. The generator is a synchronous generator with a gearbox and a direct grid connection. The wind turbine's components consist mainly of:

- *Tower*: made of concrete and galvanized steel elements. Steel parts are painted.
- *Nacelle*: including hub, steel, copper, iron and unsaturated polyester resin are the main components.
- *Blade*: each blade consists of fibreglass and epoxy resin mainly.

Energy consumption for operation has been estimated based on the Eclipse Project [13].

The life of the wind system is supposed to be 20 years. Transformer losses are about 1% and full load hours about 2628 h/year (30% of the full load of the 4.5 MW). Wind turbine produces 11.7 GWh of electricity per year. Clearly, in practical cases, the

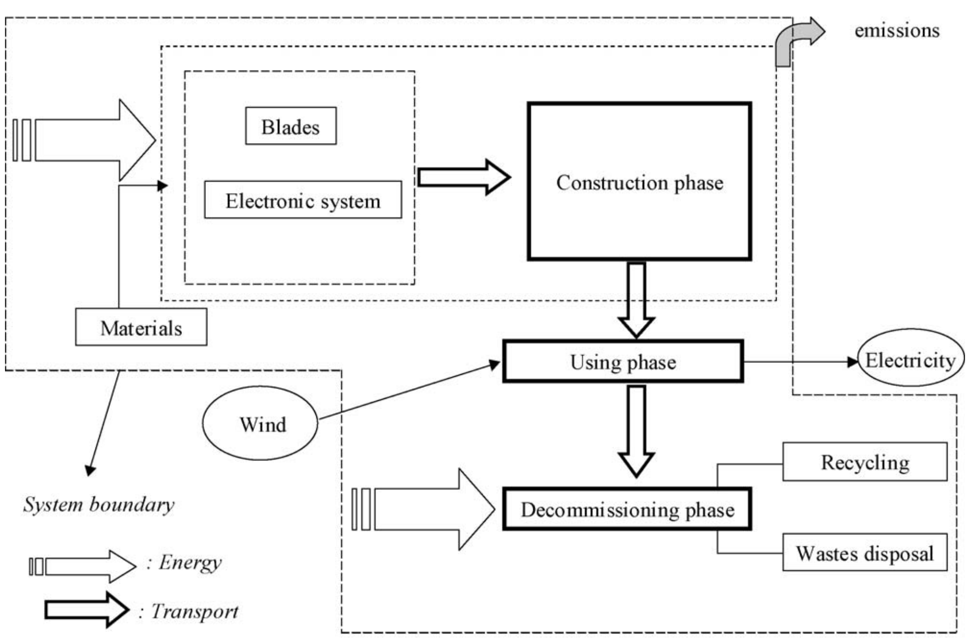

Fig. 2. Life cycle boundary of the 250 W wind turbine.

Table 1
Distance between sub-contractors and assembling factory.

Components	Distance (km)
Nacelle and blades	900
Tower and grid	1500
Foundation	100

result will depend on the quality of the site with respect to the wind resource.

The study includes the assessment of transports of components during each life cycle steps. Transports occur by 40 t trucks. The authors took into account transportation from the components construction sites to the assembling factories and from these factories to the erection site (Table 1). In this study, the distance between the assembling factories and the using site was assumed to be 170 km.

Three inspections on site per year are assumed. Therefore, transportation by diesel car 300 km/year through the life time of the turbine has been included in the model. During the average useful life of a wind turbine, it is supposed to substitute one blade and 15% of the nacelle's component. Manufacturing energy is well documented but operational energy as well as decommissioning energy are not so well known so that it is assumed that the energy consumed for operation is equal to 15% of manufacturing energy [4].

Decommissioning is an important parameter for the life cycle analysis. As compared to nuclear energy, the advantage of wind energy is that the wastes are not toxic and have no damageable impact on the environment. It is the reason why it has been assumed that 98% of blade, 90% of grid and nacelle and 90% of tower would be recycled [15] and moreover, remaining waste is disposed to a landfill. The decommissioning site is assumed to be 120 km away from the site. The foundation is disposed on a municipal waste. Energy consumed during all decommissioning phase is assumed to be equal to the manufacturing one [4].

2.2. 250 W wind turbine description

The chosen wind turbine (vertical axis) is a Windside WS-0.3C produced in Finland. Material inventory is based on manufacturer data. Two blades consist of aluminium and fibreglass. Generator and electronic system consists mainly of aluminium, copper and steel. Energy consumption has been estimated based on the Eclipse Project [13]. This wind turbine is designed to be robust and installed in an isolated site.

All components are produced locally in Finland: a value of 100 km is taken for the transport by truck inside Finland. Wind turbine is assembled in Finland (energy mix based on 30% nuclear, 24% coal, 18% hydropower, and 14% gas mainly).

Distance between manufacturer (Finland) and end user site (South France) is taken equal to 3250 km: 2030 km by boat and 1220 km by truck.

For the decommissioning phase, generator is recycled and for the other parts about 95% is recycled and remaining is disposed on landfill. Decommissioning energy is taken equal to the manufacturing energy. The decommissioning site is assumed to be 120 km away from the site in South France.

For comparison, useful life time of the small wind turbine is supposed to be equal to the large wind turbine one, i.e. 20 years. Based on manufacturer data, the turbine produces 120 kWh/year of electricity (which corresponds to a 50 W average power rather than 250 W as announced by Windside).

3. LCA results

The SimaPro software [16] is used herein to perform the life cycle analysis of the two turbines. Results are shown in Table 2.

For the four impact categories, construction phase yields the highest impact followed by transport. The operational phase has very little impact.

Adding transportation phases during construction and decommissioning yields a huge transport impact for human health since it reaches 44% for the 4.5 MW turbine. For the 250 W turbine, impact is not so bad because it was assumed that most of transportation was performed by boat. With respect to climate change and resource depletion, the impact of transportation is relatively high for the 4.5 MW turbine. It is only for the ecosystem, that transportation impact is negligible. Clearly, there is a big challenge to reduce the transportation by truck. Transportation by boat or train will have to be preferred rather than by truck.

The negative damage due to decommissioning phase is very interesting. The reason why dismantling and removal yields impacts reductions is that recycling is used to a high extent. The materials used during the construction are recovered and refunded to the technosphere by means of recycling. Included in dismantling and removal is the environmental burdens of dismantling, transport and processing of materials so that the materials are ready for new use.

It is important to note that disposal of materials is important for the environmental profile of electricity generated from wind power plant. This corresponds to one advantage of wind energy as compared to nuclear energy and it must not be underestimated. Environmental impacts will be much less favourable if recycling is not correctly performed. This positive impact of recycling is more important for the 250 W wind turbine. In this case, decommissioning phase can

Table 2
Wind turbines impacts (Impact 2002+ approach) with (a) 4.5 MW and (b) 250 W wind turbine.

	Resources depletion (GJ primary non-renewable energy)		Climate change (tequiv. CO_2)		Human health (DALY)		Ecosystem (10^3.PDF.m^2.yr)	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Construction	52,759	2.72	3173	0.16	2.94	4.2×10^{-4}	1126	34.8
Operational phase	5242	–	185	–	0.17	–	62.6	–
Transport	15,631	0.33	1170	0.02	2.08	2.2×10^{-5}	126	0.72
Decommissioning								
Transport part	1.24×10^3	0.03	93.1	2×10^{-3}	166×10^{-3}	2.1×10^{-6}	10	0.07
Energy part	4.23×10^3	0.58	40.5	5×10^{-3}	34×10^{-3}	4.6×10^{-6}	20	2.75
Decommissioning part	-8.95×10^3	−0.83	−969.5	−0.08	-264×10^{-3}	-4.5×10^{-5}	−167	−8.15
Total decommissioning	−3480	−0.22	−835.9	−0.07	-64×10^{-3}	-3.8×10^{-5}	−137.7	−5.33
Total	70,152	2.83	3692.1	0.11	5.126	4.0×10^{-4}	1177.4	30.20
Total ($kWhe^{-1}$)	3×10^{-4}	1.2×10^{-3}	1.6×10^{-5}	4.6×10^{-5}	2.2×10^{-8}	1.7×10^{-7}	5.0×10^{-6}	1.3×10^{-2}

offset the negative transport impacts and reduce construction impact (except for resources depletion).

For the 4.5 MW wind turbine, operation part of the life cycle does not have a high impact (resource impact is only 7%). In the operational phase, for the 250 W wind turbine, it was assumed that there was no external source of energy nor transport supply.

The results expressed per unit of produced electricity show that, for all categories, environmental damages are more important for the small wind turbine than for the large one.

Poorer results of the 250 W wind turbine are mainly caused by the small amount of electricity produced. Indeed, this wind turbine is designed to be robust for end users on isolated sites, so manufacturer did not optimise the aerodynamic profile to try to increase the electricity production. Sure, the optimisation of small turbines requires still R&D.

3.1. Energy consumption and GHG emissions

According to Table 2, the 4.5 MW wind turbine consumes about 70.1 TJ of primary energy in its life cycle and produces 11.7 GWh of electricity. The 250 W wind turbine consumes 2.8 GJ and produces 2 MWh of electricity. The manufacturing of the system accounted for 75% of the life cycle energy consumption for the 4.5 MW wind turbine and about 96% for the 250 W one.

Energy intensity defined as the ratio between the energy consumption and the energy production are about 0.3 MJ/kWhe or 0.08 kWhprim/kWhe for the 4.5 MW turbine and about 1.2 MJ/kWhe or 0.33 kWhprim/kWhe for case the 250 W turbine. A comparison of our figures with other published results shows that, for 70 wind plant studied [17] the energy intensity depends on the technologies and ranges between 0.0014 to 1 kWhin/kWhe for units implemented in the years 1983–2001. For a 3.0 MW wind turbine, Vestas calculates about 2.73×10^{-2} kWhin/kWhe for an onshore wind turbine [14].

It is difficult to directly compare those figures with fossil fuel power generation. However, considering a steam power station which efficiency is equal to 0.33 should yield an energy intensity equal to 3 kWhprim/kWhe just for the operational phase which is much higher than for the whole life cycle for wind energy. This corresponds exactly to the case of nuclear energy. Considering a combined cycle with an efficiency equal to 0.5 would still give a high figure for the energy intensity since it would give 2 kWhprim/kWhe. Therefore, it can be claimed that the energy intensity of wind power is excellent as compared to fossil fuel or nuclear power stations.

With respect to climate change, the CO_2 intensity is defined as the CO_2 emitted per kWh of electricity. From Table 2, we obtain 15.8 and 46.4 g CO_2/kWhe respectively for the 4.5 W and 250 W wind turbines. Ardente et al. obtained for a wind farm a CO_2 intensity index ranging from 8.8 to 18.5 g CO_2/kWhe [4]. Generally it is claimed that nuclear energy yields a little less than 10 g CO_2/kWhe and fossil fuel electricity yields, depending on the technology and on the fuel, figures ranging from 400 to 1000 g CO_2/kWhel (considering only the operational step). According to IEA [18], the world CO_2 emission is equal to 600 g CO_2/kWhel. Therefore, wind energy presents very interesting figures with respect to CO_2 emissions as compared to fossil fuel power stations and is close to that of nuclear energy.

3.2. Pay back time indexes

Although not relevant since it compares different energy kinds, we present the EPBT, ratio between the primary energy consumption during the whole life cycle and the electricity produced by the yearly wind turbine which is respectively 1.7 years and 6.5 years for the 4.5 W and 250 W wind turbines.

The primary energy pay back time is much more relevant since it is the ratio between two primary energies: the one used during the whole life cycle and the other one corresponding to the electricity production. To evaluate the primary energy corresponding to the electricity produced by the turbine, we have to make an assumption of the ratio between the electricity produced and the corresponding primary energy. Two figures can be considered: according to IEA [18], the world ratio between the global electricity production and the primary energy to produce that electricity was equal to 0.365. For the French national electric network (EDF), the efficiency is about 0.35. Those two figures are very close. Taking the EDF figure, the French electric network should have consumed 33,428 MWh/year of primary energy to produce the 4.5 MW turbine yearly electricity production and 342.9 kWh/year of primary energy for the 250 W turbine. The ratio between this equivalent primary energy production and the primary energy consumption during the whole turbine life (PEPBT) is equal respectively to 0.58 year and 2.29 years for the 4.5 MW and the 250 W wind turbines.

These figures mean that after 0.58 year, time for primary energy pay back, the 4.5 MW wind turbine produces electricity during 19.42 years without any non-renewable primary energy consumption. The energy saving for the network by the use of the wind turbine corresponds to 646 GWh of primary energy. For the 250 W wind turbine, the primary energy saving corresponds to 6 MWh.

Two approaches are presented to evaluate the CO_2 saving due to the wind turbines. The first one consists in considering the CO_2 content of the local electricity production. In the case of the French national grid, EDF (C = 66 g CO_2/kWhe [19]), the corresponding GHG pay back time is 4.8 years for the 4.5 MW wind turbine (this wind turbine allows to save about 11.7×10^6 kg of CO_2 during its whole life time) and 14 years for the 250 W wind turbine which saves 48.9 kg of CO_2 during its life time. Another approach consists in considering that CO_2 emissions as well as electricity market do not know frontiers. Therefore, the reference is not that of the local electricity production but that of the global electricity production (i.e. C = 600 g CO_2/kWhe) or at least that corresponding to the electricity trade market (i.e. C = 450 g CO_2/kWhe for Europe in case of France). With those references the figures for GHG pay back time differ highly. For global electricity production, GHG pay back time is about 0.5 year and 1.5 years for the 4.5 MW wind turbine and 250 W wind turbine respectively. If the reference is Europe, GHG pay back time is about 0.7 year and 2 years for the 4.5 MW wind turbine and 250 W wind turbine respectively.

CO_2 saved is between 101.6×10^6 and 136.7×10^6 kg for the 4.5 MW wind turbine, and between 968.6 and 1328.6 kg of CO_2 for the 250 W wind turbine, in function of the reference.

4. Sensitivity tests

4.1. Distance and transport influence

For CO_2 emission from wind turbine life cycle, transportation contribution (adding transportation for construction, operation and decommissioning) reaches 34% for the 4.5 MW wind turbine and 20% for the 250 W one (Table 2). One way to reduce CO_2 emissions for wind turbines is to revisit the transportation strategy.

Results of sensitivity tests are presented in order to study the impact of distance and type of transport.

Two cases are studied: distance increases twice (case A) and train replaces truck (case B). We consider, for case B, that train station is quite close to the end user site.

To assess the impacts of these parameters, we consider that only process of transport varies: for each case, only one parameter

Table 3
Influence of the transport in the life cycle assessment of the 4.5 MW wind turbine.

Impact category	Resources depletion (GJ primary non-renewable energy)	Climate change (tgequiv. CO_2)	Human health (DALY)	Ecosystem (10^3 PDF.m^2.yr)
Reference	70,152	3692.1	5.126	1177.4
Case A (distance variation)	87,042	4956.5	7.375	1315.3
Case B (type of transport variation)	61,271	2835.5	3.347	1085.6

Table 4
Influence of the transport on the ecoprofile of electricity for 4.5 MW wind turbine.

	Reference case	Case A (distance variation)	Case B (type of transport variation)
Energy intensity (kWhprim/kWhe)	0.08	0.10	0.07
CO_2 intensity (g CO_2/kWhe)	15.80	21.20	12.10
PEPBT (years)	0.58	0.72	0.51
GHG pay back time (years)			
C = 66 g CO_2/kWhe	4.78	6.42	3.67
C = 450 g CO_2/kWhe	0.70	0.94	0.54
C = 600 g CO_2/kWhe	0.53	0.71	0.40

Table 5
Influence of the transport in the life cycle assessment of the 250 W wind turbine.

Impact category	Resources depletion (MJ primary non-renewable energy)	Climate change (kgequiv. CO_2)	Human health (DALY)	Ecosystem (PDF.m^2.yr)
Reference	2826.1	111.5	4.0×10^{-4}	30.2
Case A (distance variation)	3216.0	141.2	4.3×10^{-4}	31.1
Case B (type of transport variation)	2500.0	85.8	3.8×10^{-4}	29.6

(distance or type of transport) varies. Transport by diesel car is still included in the operation phase.

4.1.1. 4.5 MW wind turbine

Table 3 shows results for transport. Type and transport distance is an important factor for human health, resources and climate change, as shown in Fig. 3. With all parameters constant, using train can reduce up to 20% impact on ecosystem, 30% on resources depletion, 40% on climate change and 55% on human health.

Table 4 shows the variation of ecoprofile with transport distance and type. GHG pay back time is calculated with French reference (66 g CO_2/kWhe) and international references (450 and 600 g CO_2/kWhe). Values of all indicators increase with transport distance. Train is more environmentally friendly than trucks. But in this case, train station should not be too far from the end user site: using a truck can offset positive effect of train.

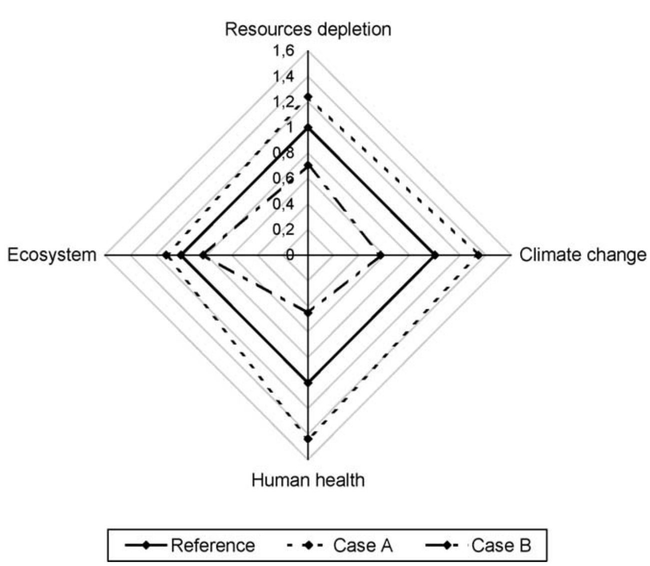

Fig. 3. Impact of sensitive test on the four categories for all the life cycle of 4.5 MW wind turbine with case A: distance variation and case B: type of transport variation.

4.1.2. 250 W wind turbine

Tables 5 and 6 show results for the 250 W wind turbine case. Variation of distance (case A) increases all categories of impact (between 27% for resources depletion and 3% for ecosystem). Using train instead of truck, decreases all categories: from 23% for climate change to 2% for ecosystem. For this small turbine, GHG pay back time is close to the life time of the system, when distance increases (Table 6) and using train reduces GHG pay back time to a half life time. If the reference for the grid emission is 450 or 600 g CO_2/kWhe, the GHG pay back time is close or less than 2 years.

The consequences of those remarks are important for a good global deployment of wind energy. Factories for building and assembling wind turbines must be distributed all around the globe so as to avoid high energy consumption in transportation.

4.2. GHG index reduction: an ideal scenario

For general public, value of the GHG index is an important parameter and manufacturers must reduce it as much as possible. Case B (changing truck by train) allows reduction of GHG index (about 12 years for the 4.5 MW turbine) but it is still large. In order to reduce GHG index significantly, we consider, for 4.5 MW turbine, case B and a new implantation site: 40% of full load is produced (instead of 30% in reference case). Moreover, distances are divided by 2.

With this scenario, GHG index is about 8.4 g CO_2/kWhe and energy intensity is 0.06 kWhprim/kWhe.

5. Analysis

The results obtained herein confirm that wind energy is a very good technology to mitigate climate change. Its energy intensity is excellent as compared to fossil fuel or nuclear energy. However, it indicates some errors to avoid in the deployment of that

Table 6
Influence of the transport on the ecoprofile of electricity of 250 W wind turbine.

	Reference case	Case A (distance variation)	Case B (type of transport variation)
Energy intensity (kWhprim/kWhe)	0.33	0.37	0.29
CO_2 intensity (g CO_2/kWhe)	46.40	58.80	35.80
PEPBT (years)	2.29	2.61	2.03
GHG pay back time (years)			
C = 66 g CO_2/kWhe	14.07	17.83	10.84
C = 450 g CO_2/kWhe	2.06	2.61	1.59
C = 600 g CO_2/kWhe	1.55	1.96	1.19

technology to be able to reach extremely low CO_2 intensity to compete with nuclear energy.

Two aspects are important to be taken into account for the implementation of wind turbines and for their management:

- Components transportation has to be as limited as possible. Factories should be distributed on the earth's surface in correlation with wind farms to be built. When, nevertheless, large distance transportation is necessary, boat or train should be preferred to truck.
- Recycling during decommissioning is an important step, not to be underestimated, to get good environmental impact figures.

With those precautions, results are excellent for the large size turbines since it may avoid large quantities of CO_2 emissions even if the reference is low carbon content electricity like it is in France (5.26×10^6 kg of CO_2 per year). If the reference is the CO_2 global emission (about 600 g CO_2/kWhe for grid emission), the avoided CO_2 emission is extremely high (about 7.02×10^6 kg of CO_2 per year).

An ideal case is presented to have a GHG index less than 10 g CO_2/kWhe using green transport like train, reducing distance and selecting a site with a good wind resource. Large size turbines should be able to compete with other low content carbon electricity production modes like hydro or nuclear electricity with respect to carbon content.

Moreover, wind energy presents, in contrast with nuclear energy, the advantage of having little impact on resources and on human health or ecosystem quality.

For small turbines, it is an excellent environmental solution for isolated sites where the reference is high CO_2 content electricity like power generation diesel engines (800 g CO_2/kWhe). For integration in low energy building, it is more probably a good solution provided local wind resource should be good enough. Nevertheless, R&D should still be performed on that product to get higher efficiency.

This study proves that wind energy is a good solution to provide electricity in rural zones not connected to the grid and should become one of the best ways to mitigate climate change.

An ultimate argument in favour of wind energy is that it is not only a low carbon content electricity but, it is also a source of energy which subtracts energy from the excess of energy existing at the earth's surface and responsible for climate change [20].

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